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Augmenting Visual Search Performance with transcranial Direct Current Stimulation (tDCS)

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Interim Report

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14. ABSTRACT
Various military personnel endure rigorous and demanding man hours designated to monitoring and locating targets in tasks such as cyber defense and intelligence, surveillance, and reconnaissance operations. These tasks are monotonous and repetitive in nature which can result in a vigilant decrement. A vigilance decrement occurs when cognitive demand exceeds the capability of the operator which results in a decrease in performance. The objective of the study was to evaluate a form of non-invasive brain stimulation known as transcranial direct current stimulation (tDCS) over the left frontal eye field (LFEF) region of the scalp in regards to performance during a visual search task. The findings suggest that both the anodal and cathodal stimulation configuration significantly improves detection accuracy during the task compared to the sham condition. In addition,, a correlation was found in relation to various eye metrics (percent of eye closure and Blinking Frequency) and the stimulation condition. Hence, the use of tDCS over the LFEF would be a beneficial countermeasure to mitigate the vigilance decrement and increase detection accuracy during a visual search task.

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Frontal eye field, sustained attention, transcranial direct current stimulation, monotonous, vigilance, percent of eye closure

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1.0 SUMMARY

Various military personnel endure rigorous and demanding man hours designated to monitoring and locating targets in tasks such as cyber defense and intelligence, surveillance, and reconnaissance operations. These tasks are monotonous and repetitive in nature which can result in a vigilant decrement. A vigilance decrement occurs when cognitive demand exceeds the capability of the operator which results in a decrease in performance. The objective of the study was to evaluate a form of non-invasive brain stimulation known as transcranial direct current stimulation (tDCS) over the left frontal eye field (LFEF) region of the scalp in regards to performance during a visual search task. Each participant completed three separate stimulation conditions on three separate days. The participants received anodal and cathodal stimulation of 2mA for a duration of 30 minutes as well as a sham condition. Each of the three conditions were randomized and conducted while performing the task. The findings suggest that both the anodal and cathodal stimulation configuration significantly improves detection accuracy during the task compared to the sham condition. In addition, a correlation was found in relation to various eye metrics (percent of eye closure (PERCLOS) and Blinking Frequency) and the stimulation condition. Hence, the use of transcranial direct current stimulation over the LFEF would be a beneficial countermeasure to mitigate the vigilance decrement and increase detection accuracy during a visual search task.

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2.0 INTRODUCTION

Human performance metrics have been evaluated in previous research studies to determine the cognitive ability of an operator during a vigilance task (Klinger, Tversky, & Hanrahan, 2011; Upadhyay & Singh, 2013; Pattyn, Neyt, Henderickx, & Soetnes, 2008). A vigilance task is described as a task that an operator can perform without difficulty for a short period of time; however as time on the task increases the operator's performance becomes impaired or degrades. This impairment of the human operator performance is known as a "vigilance decrement" (Verster & Roth, 2013). During a vigilance decrement, the operator experiences either a decrease in correct detections over time or an increase in reaction time (Helton & Russell, 2011). The vigilance decrement is commonly a result from mental demand or cognition overload during a monotonous and repetitive task (Finomore, Shaw, Warm, Matthews, & Boles, 2013). With the excess of cognitive workload on an operator, the desired performance on a specific task will begin to diminish. In military operations, cognitive performance is instrumental to ensure that the operators perform their designated tasks to their best ability. If an error occurs or a threat is not detected, it could result in serious repercussions. Operator performance has always been at the forefront of the air force mission. However with an increase in workload on the operators within the past several years, performance optimization under high cognitive workload has become a key focus. It is therefore imperative to determine if modifications to the operator's cognitive ability could result in an improvement in detection accuracy and response time during a monotonous task.

Various remedies have been evaluated in an attempt to mitigate the vigilance decrement during a monotonous task. Previous research studies have provided the operator's with chewing gum (non-caffeinated) or caffeinated beverages (Morgan, Johnson, & Miles, 2014; Temple et al., 2000) during a vigilance task in efforts to improve performance. When the operator was provided with chewing gum during a vigilance task (Morgan et al., 2014), target detection and response time improved. However, these improvements in the operator's performance were only displayed in the latter stages of the task. On the other hand, when the operator was provided with caffeinated beverages (Temple et al., 2000), the overall percent of target detection displayed a decrement. Moreover, the participants who received caffeine did perform at a higher level compared to the participants who received non-caffeinated beverages but a decrement still occurred. Both of these remedies provided positive feedback on the operator's performance compared to the sham condition. Our objective is to determine if providing non-invasive brain stimulation may prove to be a more adequate solution in reducing vigilance during a monotonous task.

A form of non-invasive brain stimulation known as transcranial direct current stimulation (tDCS) was first introduced in the medical realm. This technology was used for patients undergoing treatment for major depressive disorders (Martin et al., 2011), stroke rehabilitation (Fusco et al., 2013) and Parkinson's disease (Benninger et al., 2010), just to name a few. Findings have shown that administering tDCS improved their mental and physical capabilities at a quicker rate. As of late, there has been recent interest in the use of tDCS on healthy participants to improve human cognitive performance. The application of tDCS has been administered over the prefrontal cortex to improve working memory and accelerated learning (Hoy et al., 2013; Martin et al., 2013; Andrews, Hoy, Enticott, Daskalakis, & Fitzgerald, 2011). In a recent study, it has been

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shown that applying anodal stimulation over the dorsal-lateral prefrontal cortex accelerated the training time for image analyst (McKinley, McIntire, Bridges, Goodyear, & Weisend, 2013). This demonstrated that tDCS technology could be used to accelerate learning and reduce errors during a monotonous task. Another study was conducted using tDCS over the prefrontal cortex to enhance vigilance in operators during a repetitive task (Nelson, McKinley, Golob, Warm, & Parasuraman, 2014). The findings provided evidence that applying tDCS over the prefrontal cortex improved target detection performance.

In this study, we applied tDCS to the left frontal eye field (LFEF) region using anodal, cathodal and sham conditions during a visual search task. The frontal eye field region is involved in processing visual information (Jaun-Frutiger, Cazzoli, Müri, Bassetti, & Nyffeler, 2013). It has also been shown that attentional orienting, saccades programming, and visual search are linked to the frontal eye field activity (Ronconi, Basso, Gori, &Facoetti, 2012). Our efforts in this study attempt to mitigate the vigilance decrement by using tDCS over the LFEF region to increase functional activity. In doing so, we expect to support previous evidence that using tDCS is beneficial to cyber defense operator, air traffic controllers, remote piloted aircraft operators and the overall air force mission.

3.0 METHODS

3.1 Participants

A total of 12 active duty military participants were recruited for the study, however one of the participants withdrew. Of the 11 participants who completed the study, 6 were male and 5 were female. The age for the participants ranged from 24 to 42 years old (mean age of 31.7). The study was completely voluntary and the participants could withdraw at any time if they wished to do so. Participants were excluded from the study if they had any neurological or psychological disorders, problems with motor coordination, head trauma, high blood pressure or were color deficient. Female participants were also excluded if they were pregnant or planning to become pregnant during the duration of the study. Compensation of $20/hour was provided to the participants as well as an Air Force coin at the completion of the study.

3.2 Vigilance Task

The vigilance task that was performed during this study involved a visual search detection paradigm. The task took place in our laboratory at Wright-Patterson Air Force Base using a standard desktop computer (Samsung 173s 17” monitor). When program began, a screen appeared randomly displaying 80 blue circles and 80 red squares. Over the duration of the task, twenty-five percent of the images displayed a random red circle, this was the objective target. If the participant observed the red circle on the screen they responded by pressing the enter button on the keyboard. If they did not observe the red circle on the screen, they responded by pressing the spacebar. The images were on the screen for a duration of 7 seconds and there was a 1.5 second break between images. During the break phase, a crosshair was represented in the middle of the screen which allowed each participant to refocus before the next trial began. The overall task had a duration of 30 minutes. (See figure 1 for representation of the task.)

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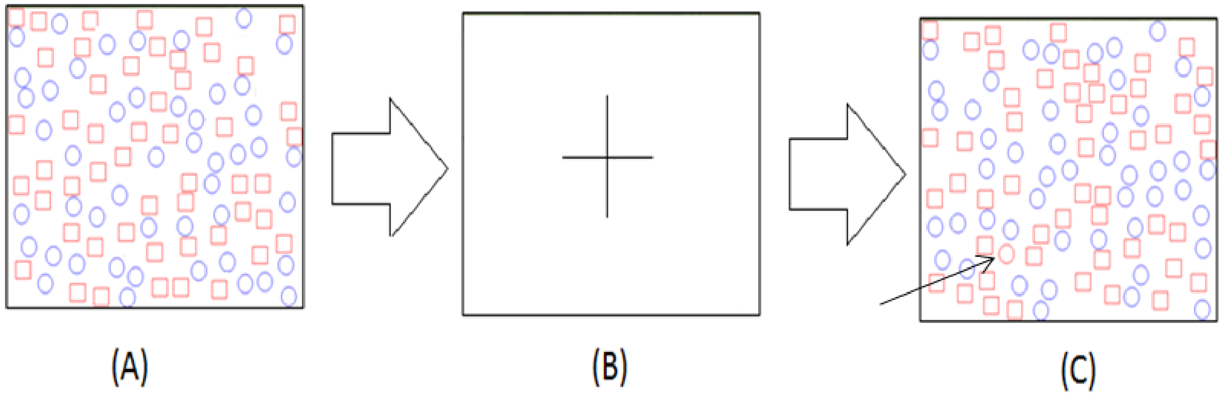

Figure 1. Example layout of the Visual Search Task Paradigm. Diagram A represents a static view without a target present, Diagram B represents a static view of the break period, Diagram C represents a static view with a target present

3.3 Equipment

<u>MagStim DC Stimulator</u>

The tDCS was administered using a MagStim DC stimulator system (MagStim Company Limited; Whitland, UK). The device allowed for a continuous current (up to 5mA) to be passed through the electrode configuration for a specified duration. In our current condition, we applied a 2mA current for a duration of 30 minutes. The MagStim DC stimulator was battery-powered and had built-in safety features to ensure the current was continuous and the impedance was within the allowable guidelines. If the impedance reached 50 kΩ, the DC stimulator would automatically shut down to reduce any risks of burns or electrical shock from occurring. Programming codes were provided to implement a double-blinded study. The programming code would either provide stimulation or sham conditions. In the sham condition the current ramped up to 2mA over a duration of 15 seconds then stayed constant for an additional 30 seconds after reaching 2mA. The current was then ramped down to zero over a duration of 15 seconds. In doing so, each participant in the sham scenarios were under the impression that they were receiving the brain stimulation during the study.

<u>tDCS Electrodes</u>

In previous research studies (Eun-Kyoung & Nam-Jong, 2011; Hauser, Rotzer, Grabner, Merillat, & Jancke, 2013; Coffman et al., 2012), wet sponge electrodes were used to administer the electrical current for tDCS. Here, we used a custom design of silver/silver chloride electroencephalographic (EEG) electrode. The custom designed electrodes represented greater stability over time, produced lower sensations over time, and displayed less skin irritation when compared to wet sponge electrodes (Petree, Bullard, Jung, & Paulson, 2011). The electrode configuration consisted of a 5 EEG array electrode design. The electrical current was passed

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between two 3cm x 5cm ($35cm^2$) conductive EEG electrodes. When 2mA was supplied from the MagStim DC stimulator, the average current density was 0.199 $\frac{mA}{cm^2}$.

<u>Transcranial Direct Current Stimulation (tDCS)</u>

Three various electrode configuration paradigms were implemented in the experimental design (anodal, cathodal and sham stimulation). When the participants received anodal stimulation, the anode electrode was placed over the left frontal eye field (LFEF). If the participant receives cathodal stimulation, the cathode electrode was placed over the LFEF (See figure 2). The electrical current modifies the cortical excitability of the neurons, in turn altering the resting membrane potential. Anodal tDCS produced a transient increase in cortical excitability, whereas the cathodal stimulation caused a short-term reduction in cortical excitability (Hendy & Kidgell, 2013). Each of the participants performed three days of stimulation (anodal, cathodal, sham conditions) and the sequential order was randomized.

Figure 2. The tDCS electrode configuration over the left frontal eye field (LFEF) region of the scalp

<u>FaceLab</u>

The eye-tracking system used in this study was FaceLab. FaceLab was a real-time off body eye tracking system that has the capability to record eye movement, blink frequency and duration, percent of eye closure (PERCLOS) and head positioning. The recorded eye metrics were analyzed and correlated in relation to the participant's performance during the task. The FaceLab system consisted of two cameras and an infrared source which are placed under the computer monitor. A sampling rate of 60Hz was employed during the recording of each participant's eye metrics. In order for FaceLab to effectively track the pupil, a distance of 32 inches from the nasion to the center of the screen was required.

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3.4 Procedures

The study took place over four separate days. On day one, each of the participants were provided with a verbal overview involving the contents and description of the study. If they wished to participate, each participant signed an informed consent document (ICD) which stated the appropriate information and background involving non-invasive brain stimulation. An Initial Screening Questionnaire was provided to gather background information for eligibility. If the participants met the inclusion criteria, they were able to continue forward in the study. Following completion of the overview and forms, training on the task would begin. First, a ten minute verbal feedback training session was performed. During this session, the participants would be provided with verbal feedback on their responses immediately following the visual search paradigm. If they responded correctly to the image, they would hear "Hit". If they responded incorrectly to the image, they would hear "False Alarm". Lastly, if the participant did not respond to the image, they would hear "Miss". Following the ten minute training session of the task, each participant would be provided with a short break before completing the main task session. The main task was similar to the training session, however the main task session was 30 minutes in duration and there was no verbal feedback on their response. Once the main task session was completed, each participant was able to leave for the day. It is important to note that there is no stimulation on day one, this day was comprised strictly for training purposes. Moreover, day two, three and four entailed providing non-invasive brain stimulation during the task in one of three conditions (anodal, cathodal or sham). Each of the participants experienced all three conditions; however the sequence of stimulation was randomized per participant.

4.0 RESULTS

The results from the study were divided into two separate sections: Accuracy and Eye Metrics. First, the accuracy section covers the analysis and results of the correctly detected targets for each treatment condition with respect to the time on the task. Second, the eye metrics section details the analysis of the blinking frequency and PERCLOS eye metrics for each treatment condition with respect to time on the task.

4.1 Analysis for Accuracy

To examine the effects of tDCS on visual search accuracy, an Analysis of Variance was conducted with factors Condition, Time, and the interaction of Condition and Time. The condition variable had three levels: sham, anodal, and cathodal stimulation. The time variable was defined as 10 minute intervals during the 30 minute task (0-10min, 10-20min, 20-30min). The ANOVA did not reveal a significant main effect of condition ($F(2,22) = 0.95$, $P = 0.4034$) or time ($F(2,22) = 2.97$, $P = 0.0724$) on visual search accuracy. However, there was a significant interaction between condition and time ($F(4,44) = 3.42$, $P = 0.016$).

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Table 1. ANOVA depicting the relationship between the main factors for the accuracy analysis

Source	DF	SS	DFe	SSe	F	p
Condition	2	132	22	1538	0.95	0.4034
Time	2	235	22	872	2.97	0.0724
Condition*Time	4	522	44	1676	3.42	0.0160*

Note: * Represents statistical significance at an alpha level of 0.05

To examine the differences in accuracy means between the stimulation conditions at each time interval, a series of paired t-tests were conducted (see Table 2). There was a statistically significant difference in accuracy between anodal and sham stimulation condition during the 10-20 minute time interval (t = -2.84, P = 0.0161). The change in performance from each time period to the following time period was then compared using a series of paired t-tests. This was done to examine changes in performance over time for each of the three conditions. Table 3 displays the results. The sham stimulation condition shows a statistically significant change in accuracy from 0-10 minutes to 10-20 minutes time interval (t = -2.35, P = 0.0383) and from 0-10 minutes to 20-30 minutes time interval (t = -3.29, P = 0.0072). The mean accuracies for the sham condition were M = 83.9 (SEM = 3.7), M = 78.0 (SEM = 2.5) and M = 77.4 (SEM = 2.2) during the 0-10min, 10-20min and 20-30min time intervals, respectively. Additionally, the anodal condition exhibited a statistically significant change from 0-10 minutes to 10-20 minutes (t = 3.46, P = 0.0054) and from 10-20 minutes to 20-30 minutes (t = -2.43, P = 0.0334). The mean accuracies for the anodal condition were M = 79.9 (SEM = 2.9), M = 87.0 (SEM = 2.6) and M = 80.1 (SEM = 2.5) during the 0-10min, 10-20min and 20-30min time intervals, respectively. Finally, the mean accuracies for the cathodal condition were M = 82.4 (SEM = 1.5), M = 82.7 (SEM = 2.3) and M = 80.1 (SEM = 2.9) during the 0-10min, 10-20min and 20-30min time intervals. Figure 3 provides a graphical representation of the accuracy means with respect to condition and time.

Table 2. Paired t-test results comparing the conditions at each time interval for the accuracy analysis

Time	Condition		Mean Accuracy		Mean	Two-Tailed Paired t-test		
	Level 1	Level 2	Level 1	Level 2	Diff	n	t	p
0-10min	Sham	Anodal	83.91	79.85	4.06	12	1.26	0.2330
	Sham	Cathodal	83.91	82.36	1.55	12	0.42	0.6793
	Anodal	Cathodal	79.85	82.36	-2.51	12	-0.84	0.4215
10-20min	Sham	Anodal	77.97	87.02	-9.05	12	-2.84	0.0161*
	Sham	Cathodal	77.97	82.70	-4.74	12	-1.60	0.1390
	Anodal	Cathodal	87.02	82.70	4.31	12	1.84	0.0932
20-30min	Sham	Anodal	77.35	80.13	-2.78	12	-1.43	0.1808
	Sham	Cathodal	77.35	80.13	-2.78	12	-1.02	0.3304
	Anodal	Cathodal	80.13	80.13	-0.00	12	-0.00	0.9999

Note: * Represents statistical significance at an alpha level of 0.05

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Table 3. Paired t-test results comparing the significance of change from one time interval to a following time interval for the accuracy analysis

Condition	Time Change	Accuracy Mean Change	Accuracy SEM Change	Two-Tailed Paired t-test n	t	p
Sham	first to second	-5.94	2.53	12	-2.35	0.0383*
	first to third	-6.56	1.99	12	-3.29	0.0072*
	second to third	-0.61	1.72	12	-0.36	0.7282
Anodal	first to second	7.16	2.07	12	3.46	0.0054*
	first to third	0.28	2.24	12	0.12	0.9040
	second to third	-6.89	2.83	12	-2.43	0.0334*
Cathodal	first to second	0.34	2.23	12	0.15	0.8817
	first to third	-2.23	3.08	12	-0.72	0.4840
	second to third	-2.57	3.57	12	-0.72	0.4868

Note: * Represents statistical significance at an alpha level of 0.05

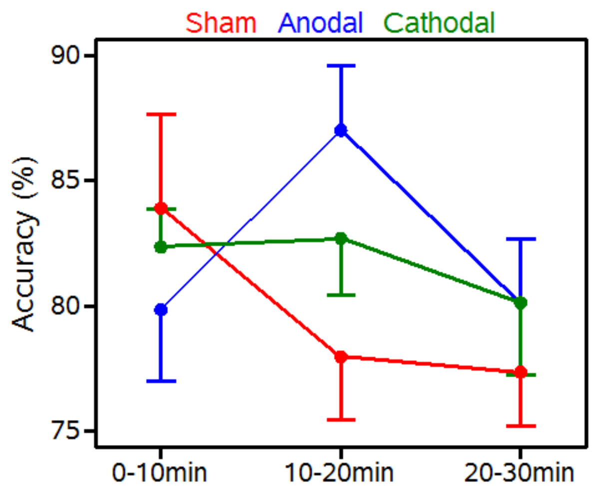

Figure 3. Accuracy plot displaying each of the three conditions with respect to the 10 minute time intervals

4.2 Analysis for Eye Metrics

It's important to note that a few participants were unable to have their pupils successfully tracked by the FaceLab system. For this reason, data from nine participants for the sham condition and eight participants for both the anodal and cathodal conditions were evaluated and analyzed. Similar to the visual search accuracy analysis, blinking frequency and PERCLOS were evaluated using an ANOVA with factors Condition, Time, and the interaction of Condition and Time. The

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time and condition variables were described in the previous analysis section. The results are presented in Table 4. There was no significant main effect of time on blinking frequency ($F(2,16) = 0.36$, $P = 0.7054$). In addition, the interaction between condition and time failed to achieve statistical significance ($F(4,31) = 2.36$, $P = 0.0752$) for blinking frequency. However, there was a significant main effect of stimulation condition on blinking frequency ($F(2,15) = 6.66$, $P = 0.0083$). As seen in table 4, there was no significant effect of on PERCLOS ($F(2,16) = 0.34$, $P = 0.7192$). There was, however, a significant main effect of condition ($F(2,15) = 5.71$, $P = 0.0140$) and a significant interaction between condition and time ($F(4,31) = 2.92$, $P = 0.0369$) on PERCLOS.

Table 4: ANOVA depicting the relationship between the main factors for the eye metric data

Dependent Variable	Source	DF	DFe	F	p
Blink Frequency	Condition	2	15.2	6.66	0.0083*
	Time	2	16.1	0.36	0.7054
	Condition*Time	4	30.7	2.36	0.0752
PERCLOS	Condition	2	15.3	5.71	0.0140*
	Time	2	16.2	0.34	0.7192
	Condition*Time	4	30.8	2.92	0.0369*

Note: * Represents statistical significance at an alpha level of 0.05

Table 5 displays two tailed paired t-tests comparing the conditions at each time interval for blinking frequency and PERCLOS. There was a significant difference in blinking frequency between anodal and sham condition ($t = -4.49$, $P = 0.0020$) and between anodal and cathodal condition ($t = 3.23$, $P = 0.0145$) during the 0-10 minute time interval. Additionally, there was a significant difference in blinking frequency between the anodal and sham condition ($t = -3.20$, $P = 0.0126$) and between anodal and cathodal condition ($t = 3.15$, $P = 0.0161$) during the 10-20 minute time interval. Mean blinking frequencies for the anodal condition were M = 17.6 (SEM = 1.5), M = 17.9 (SEM = 2.0) and M = 16.2 (SEM = 2.2) during the 0-10min, 10-20min and 20-30min time intervals, respectively. The mean blinking frequencies for cathodal stimulation were M = 11.6 (SEM = 1.5), M = 12.3 (SEM = 2.4) and M = 13.8 (SEM = 1.9) during the 0-10min, 10-20min and 20-30min time intervals. For sham stimulation, the mean blinking frequencies were M = 12.3 (SEM = 1.3), M = 11.9 (SEM = 1.9) and M = 13.9 (SEM = 2.3) during the 0-10min, 10-20min and 20-30min time intervals, respectively.

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Table 5. Paired t-test results comparing the conditions at each time interval for the Blinking Frequency and PERCLOS

Dependent Variable	Time	Condition		Mean		Mean Diff	Two-Tailed Paired t-test		
		Level 1	Level 2	Level 1	Level 2		n	t	p
Blink Frequency (blinks/min)	0-10min	Sham	Anodal	12.3	17.6	-5.3	9	-4.49	0.0020*
		Sham	Cathodal	12.7	11.8	0.9	8	0.42	0.6841
		Anodal	Cathodal	17.8	11.8	5.9	8	3.23	0.0145*
	10-20min	Sham	Anodal	11.9	17.9	-5.9	9	-3.20	0.0126*
		Sham	Cathodal	11.9	12.5	-0.6	8	-0.27	0.7977
		Anodal	Cathodal	18.3	12.5	5.9	8	3.15	0.0161*
	20-30min	Sham	Anodal	13.9	16.2	-2.3	9	-1.47	0.1802
		Sham	Cathodal	13.5	13.8	-0.3	8	-0.20	0.8504
		Anodal	Cathodal	16.4	13.8	2.6	8	1.80	0.1150
PERCLOS	0-10min	Sham	Anodal	3.7	5.5	-1.8	9	-4.85	0.0013*
		Sham	Cathodal	3.9	3.7	0.2	8	0.29	0.7797
		Anodal	Cathodal	5.6	3.7	1.9	8	2.80	0.0264*
	10-20min	Sham	Anodal	3.7	5.7	-2.0	9	-3.10	0.0147*
		Sham	Cathodal	3.7	4.0	-0.3	8	-0.49	0.6373
		Anodal	Cathodal	5.9	4.0	1.9	8	2.52	0.0397*
	20-30min	Sham	Anodal	4.2	5.0	-0.8	9	-1.62	0.1430
		Sham	Cathodal	4.1	4.4	-0.3	8	-0.76	0.4727
		Anodal	Cathodal	5.1	4.4	0.7	8	1.12	0.3016

Note: * Represents statistical significance at an alpha level of 0.05

Our analyses also revealed a significant main effect of condition on PERCLOS (F(2,15) = 5.71, P = 0.0140) and a significant interaction between condition and time (F(4,30) = 2.92, P = 0.0369) with respect to PERCLOS. The PERCLOS means were M = 5.5 (SEM = 0.5), M = 5.7 (SEM = 0.6) and M = 5.0 (SEM = 0.6) during the 0-10min, 10-20min and 20-30min intervals for anodal stimulation. For cathodal stimulation, the PERCLOS means were M = 3.6 (SEM = 0.4), M = 3.9 (SEM = 0.7) and M = 4.4 (SEM = 0.6) during the 0-10min, 10-20min and 20-30min intervals. Finally, the PERCLOS means for sham stimulation were M = 3.7 (SEM = 0.4), M = 3.7 (SEM = 0.5) and M = 4.2 (SEM = 0.6) during the 0-10min, 10-20min and 20-30min intervals, respectively. Paired t-tests revealed a significant difference in PERCLOS between the anodal and sham condition (t = -4.85, P = 0.0013) and between the anodal and cathodal condition (t = 2.80, P = 0.0264) during the 0-10 minute time interval. Further, there was a significant difference in PERCLOS between the anodal and sham condition (t = -3.10, P = 0.0147) and between the anodal and cathodal condition (t = 2.52, P = 0.0397) during the 10-20 minute time interval. The blinking frequency means are displayed in Figure 4 while the PERCLOS means are depicted in Figure 5 for each condition and time interval.

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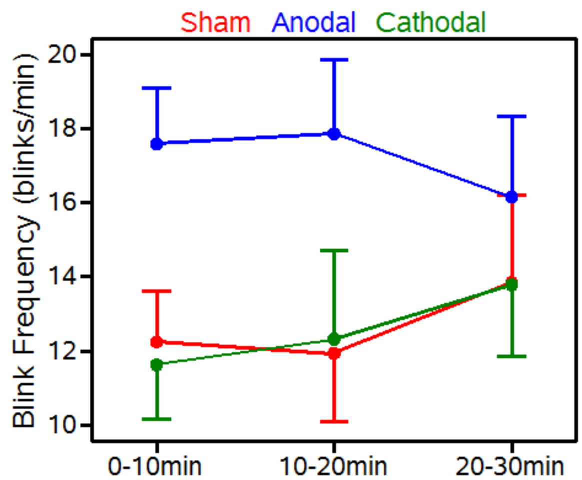

Figure 4. Blinking Frequency plot displaying each of the three conditions with respect to the 10 minute time intervals

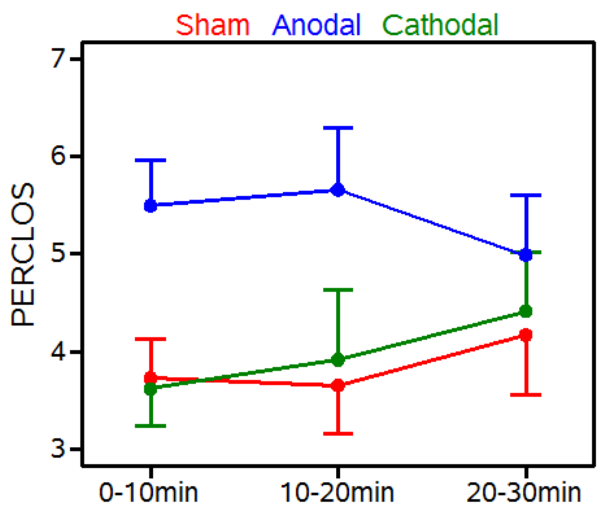

Figure 5. PERCLOS plot displaying each of the three conditions with respect to the 10 minute time intervals

5.0 DISCUSSION

Similar to the results section, the discussion was segregated into two separate sections for the performance and eye metric variables.

5.1 Accuracy

The ability to locate and detect targets among distractors quickly and efficiently is instrumental within a variety of tasks in the Air Force. As operators move toward supervisory tasks, critical targets or pieces of information are often infrequent. With infrequent targets, performance tends to decline as the time on the task increases (i.e. the vigilance decrement (Lara, Madrid & Correa,

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2014; Wiggins, 2011; McIntire, McKinley, McIntire, Goodyear, & Nelson, 2013)). This performance decline is primarily in the form of decreased target detection which may result in serious repercussions. In this study, our objective was to examine the effects of transcranial direct current stimulation over the left frontal eye field region to improve visual search and detection accuracy.

Our results indicate that anodal and cathodal stimulation applied to a scalp location over the LFEF provides an improvement in detection accuracy compared to the sham stimulation condition. Importantly, this effect varies with time. Our data suggest the effect is strongest in the second 10 minutes of the task. Specifically, anodal stimulation only exhibited a significant improvement in target detection accuracy of approximately 8% over the sham condition during the 10-20 minute time interval. It is notable that the anodal group's accuracy significantly improved by approximately 8% from the 0-10 to 10-20 minute time interval while the sham group's mean significantly declined by about 6%. Hence, extent of the effect may have been partially masked by a small, but not statistically significant difference in initial performance (i.e. 10-20 minute interval). While there were no significant differences in accuracy across the stimulation conditions for the 20-30 minute interval, it should be noted that the performance during sham stimulation significantly declined over the 30 minute task (i.e. there was a measureable vigilance decrement) while the accuracy in the anodal stimulation group did not. Hence, although there were no significant differences in the means during the final time interval, the data does support the idea that tDCS prevented a decline in performance due to time on task. In future studies, we suggest baseline performance is measured prior to the initiation of the stimulation. The data can then be normalized to the baseline to examine the extent to which tDCS influences changes in performance rather than the absolute means.

While there were no statistically significant differences in mean target detection accuracy between sham and cathodal stimulation, performance over time did not significantly change from the baseline value for participants receiving cathodal tDCS. Specifically, there were no significant differences in any of the comparisons between the 3 times points. This data provides insight that when providing anodal and cathodal stimulation over the LFEF, visual search performance increases or remains consistent during the 30 minute task. Hence, the vigilance decrement is mitigated. As previously noted, the performance conditioned to significantly decline at each time point, demonstrating a time on task effect (i.e. vigilance decrement). Consequently, the data suggest that both anodal and cathodal tDCS eliminated the performance declines over time. Temporary, yet significant improvements in target detection accuracy were also exhibited only with anodal stimulation in the second ten minutes of the task.

Importantly, these results are nearly identical to the findings from our first examination of the effects of tDCS on vigilance performance (Nelson, McKinley, Golob, Parasuraman, & Warm, 2014). While the duration of the task was longer in our original study (40 minutes vs. 30 minutes) and the tasks differed, the anodal stimulation exhibited the same temporary improvement in target detection accuracy that dissipated in the next 10 minute interval. Further, our original study showed that both anodal and cathodal tDCS prevented the decline in performance over time, just as in the study described herein. One important difference between the studies was that the original study (Nelson et al., 2014) included a baseline measure of performance that was then used to convert the data into a percentage change from the baseline to

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normalize the data, whereas our current study did not. Because performance may differ across days as a result of a variety of factors such as time of day, level of fatigue, stress, etc., normalizing the data reduces the influence of these factors and provides a clearer indication of differences in trends over time. Another interesting point is that tDCS was applied bilaterally to F3/F4 the original experiment, whereas here we used LFEF with the reference electrode applied to the contralateral bicep. The scalp locations are relatively close to each other and the electrodes provide a relatively large and diffuse area electrical field potential within the brain (Datta et al., 2009). This may therefore provide initial evidence that the effect on vigilance is not overly sensitive to precise electrode placements on the scalp or a particular electrode montage. Furthermore, the effect appears to not be task specific, provided that the task utilized tests the same cognitive skill.

Our study did not uncover any changes in reaction time. A study using another form of non-invasive brain stimulation called transcranial magnetic stimulation (TMS) was also unable to find changes in reaction times that were likely due to ceiling effects (Nelson et al., 2014). Because the task included a limited time window to search each image, we believe ceiling effect is also the cause of this finding in our study.

5.2 Eye Metrics

Previous research has shown that a variety of eye metrics such as percent of eye closure (PERCLOS) and blinking frequency are correlated with an individual’s vigilance performance level (McIntire et al., 2013). In our current study, we evaluated both PERCLOS and blinking frequency to determine if such trends existed in our testing paradigm.

The FaceLab software was implemented to record the pupils of each participant during the task. From the information collected, the blinking frequency and PERCLOS data were analyzed. The blinking frequency represented in figure 4 shows that when participants received anodal stimulation, their blinking frequencies were significantly higher compared to the cathodal and sham conditions. Because anodal stimulation yielded significant improvements in performance and prevented a measurable vigilance decrement, it appears the increased blink frequency may be associated with improved performance (i.e. higher and more consistent target detection accuracy). Our data supports a previous finding by Caffier (Caffier, Erdmann, & Ullsperger, 2003). They concluded that when performing a mental search task, an increase in blinking frequency was correlated with an alert mental state whereas a decrease in blinking frequency was correlated to a drowsy mental state (Datta et al., 2009). Additionally, high workload visual search tasks require continuous eye movement, and these eye movements are often associated with eye blinks. For example, Tsai, Viirre, Strychacz, Chase, and Jung (2007) found that blink frequency increased during a visually demanding driving task but not for a simpler version of the task. The theory is that the saccade is embedded in the eye blink itself. Hence, each blink coincides with eye movement to a new region of interest. Given the difficulty of the task and the time stress of searching the image, it is possible that the increased blink frequency detected with anodal stimulation was caused by an increased scan rate, with each blink indicating a new eye movement to a different section of the screen. Moreover, participants with a higher blinking frequency displayed a higher target detection performance.

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The data also suggests that tDCS has an effect on PERCLOS. The results show that anodal stimulation exhibited the largest PERCLOS over the duration of the task. PERCLOS has been previously correlated with the vigilance decrement, where lower vigilance performance was associated with larger PERCLOS measurements. However, the PERCLOS value in the anodal condition was relatively small (under 10% for the duration of the trail). A pervious study revealed that a missed response seldom occurred when the PERCLOS value was less than 11.5% (Abe et al., 2011). Hence, most of the errors that occur as a result of low vigilance can be mitigated when the PERCLOS is lower than 11.5%.

6.0 CONCLUSION

The current study evaluated the efficacy of tDCS to augment human performance during a visual search task. Our results indicated that the use of anodal and cathodal tDCS over the LFEF improves target detection accuracy during a visual search task. A significant difference was observed between the anodal and sham conditions for the 10-20min time interval showing a 9% difference in target detection. Additionally, both the anodal and cathodal conditions prevented a significant decline in performance caused by time on task. This finding is important to note because the vigilance decrement was dramatic for the sham condition across the duration of the task. These results are analogous to our previous work that provided initial evidence tDCS can mitigate the vigilance decrement, even though the task, stimulation duration, and electrode placement varied between the two experiments. The results suggest that the effects on vigilance are repeatable, and the short-term effects are relatively insensitive to small changes in electrode position, electrode montage, and the performance task utilized.

The eye metrics parameters that were evaluated (Blinking Frequency and PERCLOS) showed mixed results. Blinking frequency was significantly elevated during anodal tDCS of the LFEF, suggesting a higher visual search activity. Conversely, the PERCLOS was very small across the duration of the task and did not yield any insights into the performance of the participants. This conflicts with previous work showing a relationship between eye metrics and vigilance performance. It is possible that other eye metrics not examined here would yield such relationships.

Future research should examine the longevity of the effect of non-invasive brain stimulation on vigilance. It was observed in this study, that the performance for the participants that received anodal and cathodal stimulation remained level or improved during the 30 minute task. However, could this cognitive improvement continue past the 30 minute task? A study conducted by McIntire, McKinley, Goodyear, and Nelson (2014) provided evidence which showed that 30 minutes of tDCS at 2mA had a cognitive benefit that lasted the duration of the study, roughly six hours. Future research will examine the longevity of effect of tDCS on vigilance to optimize timing of the delivery and support Airman performance.

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